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Spallation neutron production in the new Dubna transmutation assembly

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Abstract

A large Pb target with a U blanket was irradiated with 1.5 GeV protons at the Dubna Nuclotron accelerator. Solid-state nuclear track detectors measured neutron spatial distributions in the new experimental transmutation assembly. Slow and fast neutron components were studied inside sections of the setup and on the U blanket surface. Neutron distributions after Cd and polyethylene shielding were also investigated. The results show that the new arrangement is efficient for transmutation experiments by (n, f) and (n,xn) reactions as well as by (n, γ) reactions.

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Keywords: Subcritical assembly; Neutron detection; Transmutation

1. Introduction

A new subcritical Pb–U assembly has been designed for experiments in Dubna by the motivation to perform experiments on increasing safety nuclear power engineering and transmutation of radioactive waste. Such experiments have been performed in Dubna during the last decade by using a large cylindrical Pb target [1,2]. Proton beams in the GeV range were used for irradiations on Pb and Pb plus U targets. The design of this setup includes a paraffin moderator to shift the spallation neutron spectrum to lower energies, because the part of the neutron spectrum at the resonance region is very important for transmutation experiments via (n, γ) reactions. In addition, fast neutrons can be used for the same purpose via (n,xn) and (n, f) reactions. To favor fast neutron production, a composite target is preferred, as was concluded from the previous experiments [3,4]. On this basis, a new experimental setup considered as a model for a core of an electronuclear reactor [5] has already been designed and first experiments with 1.5 GeV proton beams were run during the last 2 years.

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The measured neutron flux distributions in and around the aforementioned setup by solid-state nuclear track detectors (SSNTDs) are presented in this work, in order to confirm the efficiency of the new arrangement for transmutation experiments. An investigation of the neutrons escaping the setup shielding (Cd plus polyethylene) is also presented.

2. Experimental

The new transmutation assembly, as shown in Fig. 1a, consists of a cylindrical Pb target 52 cm in length and 8 cm in diameter. Around the Pb target, U rods are placed hexagonally. Each U rod is a cylinder 10.4 cm in length and 3.6 cm in diameter. Four sections of this U blanket were needed to cover the target. In Fig. 1b, a cross-section of the setup is shown with the positions of the SSNTDs indicated. The shielding consists of 1 mm Cd and about 10 cm of granulated polyethylene. Experiments were performed at the Nuclotron accelerator (High Energy Laboratory) in Dubna, using a 1.5 GeV proton beam with an integrated flux 10^{11}.

Neutron flux measurements inside the U blanket sections and on its surface as well as on the top of the shielding were performed (Fig. 1b). Inside sections, 12 sets of SSNTD detectors were placed along the diagonal of the hexagon. On the surface of the U blanket, four sets of SSNTD were positioned in the vertical direction relative to the axis of the target. At the corresponding positions on the top of the shielding, three sets of SSNTD were placed to measure the neutrons escaping the setup.

Each set of SSNTDs contains CR39 detectors that act as particle detectors in contact with Kodak LR115 Type 2B partially covered by 1 mm Cd. So each set was able to detect thermal–epithermal and intermediate–fast neutrons at the same positions. In addition, a free CR39 foil was also used in each set to detect proton recoils and give supplementary information about fast neutrons in the energy range of $0.3 < E_n < 3$ MeV, which is the range with about constant response to protons [6]. Details on the operation of these systems and their response are given in Ref. [7].

Sets of SSNTDs as fission detectors were placed outside of the middle sections of the U blanket for measuring neutrons above 1 MeV. The detectors consist of about 1 mg cm^{-2} of ^{238}U evaporated on Macrofol. Details of the method are given in Ref. [8].

3. Results and discussion

Neutron flux distributions (n cm^{-2} per proton) between sections of the U blanket are presented in Fig. 2 as a function of the radial distance from the center of the Pb target. These neutron distributions are attributed to fast neutrons. Thermal neutrons were not detected so their contribution is lower than the detection limit of the detector (10^5 n cm^{-2}). In all cases the neutron production is high in the target center and drops off towards the U blanket surface. At the first two gaps, the neutron flux falls rather more sharply than at the last gap. The behavior can be attributed to the angular distribution of the secondary particles (more abundant at wide angles). At the second gap, the neutron flux is slightly higher than in the first gap, showing an accumulation of secondary particles (build-up effect). For the last gap, the neutron distribution is quite different because protons come to rest at about 30 cm into the target. The neutron production from the central region of the target is reduced in the last gap because there are no more primary reactions and the detected neutrons come from secondaries in and around the forward direction. The different origin of these neutrons has also been confirmed by the results of a fitting process on the neutron flux distributions. According to Table 1, the neutron flux distribution at the last gap is described well by the exponential form $y = Ae^{Bx}$, in contrast to the first two gaps where a power law $y = Ax^B$ applies.

At larger distances from the target center, neutron fluxes coincide with measurements on the surface of the U blanket. Among the four sets of detectors placed on each section, significant variations were not observed, so the results given

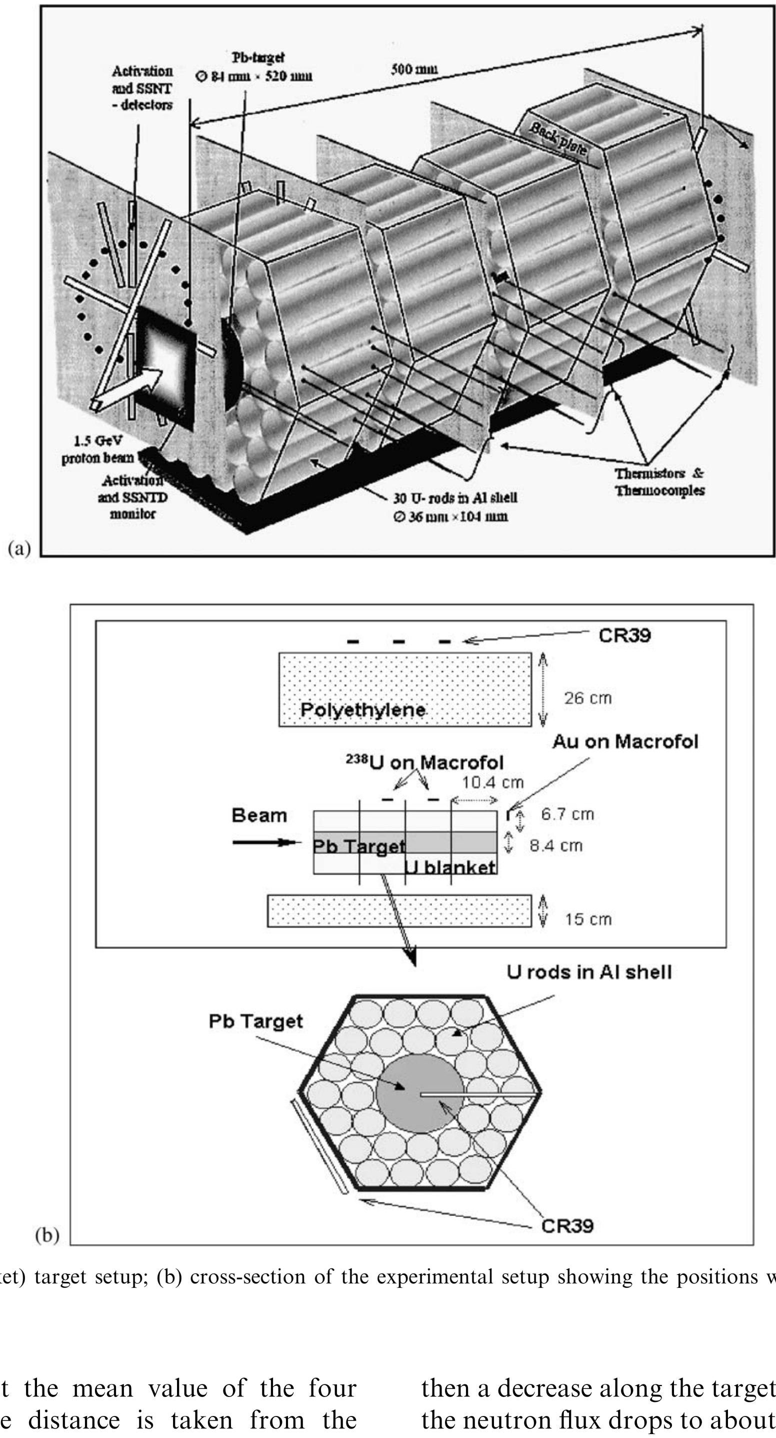

Fig. 1. (a) Pb (U-blanket) target setup; (b) cross-section of the experimental setup showing the positions where the SSNTDs were placed.

in Fig. 3 represent the mean value of the four measurements. The distance is taken from the beam entry in the target. In those positions thermal and fast neutrons were detected, both showing a small increase up to about 18 cm and then a decrease along the target. At the last section the neutron flux drops to about 40% of its value in Section 1. The neutron flux on the U blanket reflects neutron production along the target, keeping in mind that the beam diameter is small

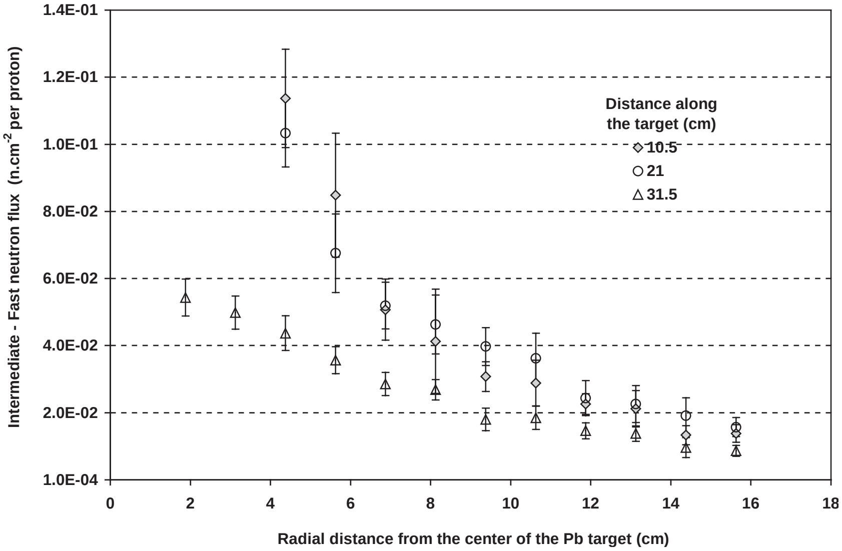

Fig. 2. Fast neutron distribution between sections of the U blanket as a function of the radial distance from the center of the Pb target.

Table 1
Fitting parameters describing the drop-off of neutron flux in the gaps between sections of the U blanket as a function of the radial distance from the center of the Pb target

Distance along the target (cm)	Fitting model (r^2)	Parameter A	Parameter B
10.5	$y = Ax^B$ (98%)	1.26 ± 0.19	-1.61 ± 0.09
21	$y = Ax^B$ (98%)	0.71 ± 0.08	-1.33 ± 0.07
31.5	$y = Ae^{Bx}$ (99%)	0.073 ± 0.002	-0.13 ± 0.01

relative to the Pb target diameter. In Fig. 3, it is obvious that half of the fast neutrons leaving the Pb target reach the U blanket surface. Thermal and epithermal neutrons are one order of magnitude less than fast neutrons. The neutron flux measured by fission detectors on the surface of the second and third sections of the U blanket is presented in Table 2. For comparison, measurements of proton recoils on CR39 at the same positions are also given. There is a good agreement between the two methods considering the different energy ranges covered by each method.

The flux of thermal and fast neutrons escaping the shielding was measured by three sets of CR39 detectors placed on the top of the polyethylene shielding across the Pb target axis. The fluxes measured by each set show no significant variations so the results given in Fig. 4 represent the mean value of the three sets. The total number of escaping neutrons is at least an order of magnitude less than on the U blanket surface and half the neutrons are in the thermal energy range. Taking into account that 1 mm of Cd is sufficient to absorb thermal neutrons coming from the target; the polyethylene shielding proves to be an efficient moderator thermalizing a large part of the fast neutrons leaving the U blanket. However, neutrons up to 3 MeV were also detected, and in forthcoming experiments the contribution of high-energy neutrons emitted mainly in the forward direction should be measured using U and Au fission detectors.

Summarizing, the fast neutron flux produced on the U blanket surface of the new transmutation assembly is an order of magnitude higher than that produced at the middle of the cylindrical Pb target with a paraffin moderator [1,2]. Also, the thermal–epithermal neutron flux in the new setup is about two times lower than measured in the Pb (paraffin) target. Therefore, the new installation appears to be more efficient for transmutation processes via

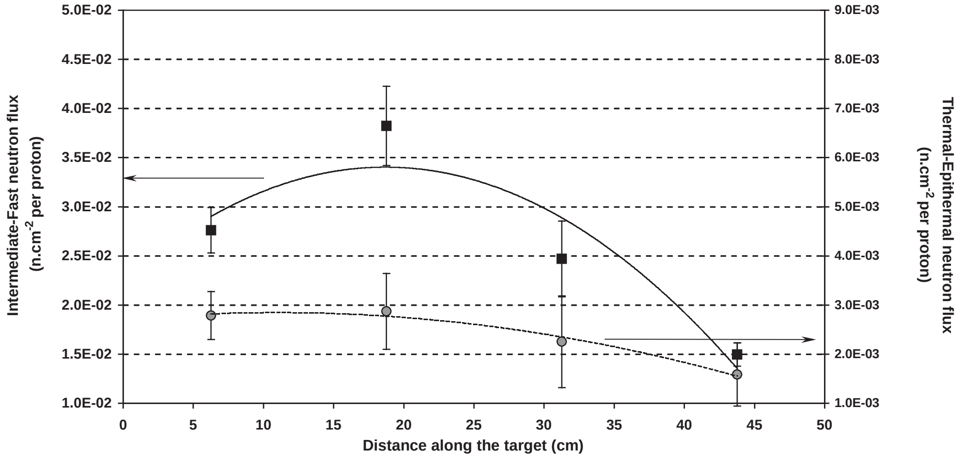

Fig. 3. Thermal and fast neutron distribution on the surface of the U blanket. Each point corresponds to a successive section of the setup.

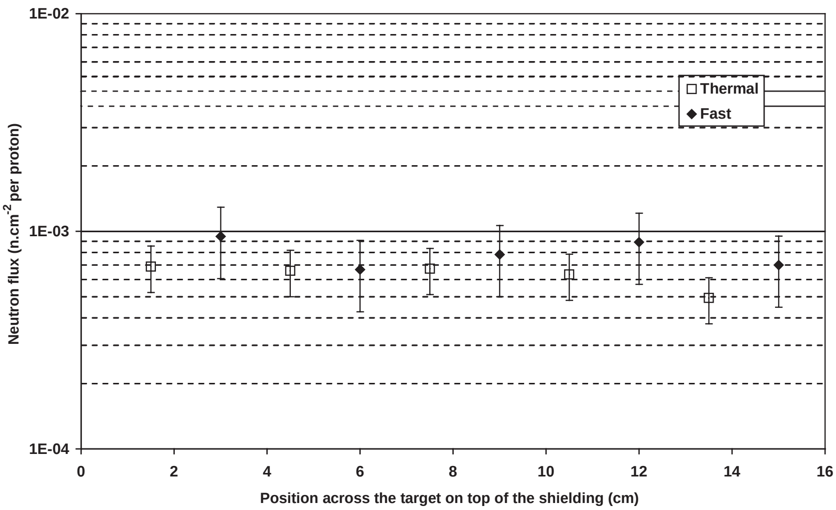

Fig. 4. Thermal and fast neutron distributions on the top of the shielding.

Table 2
Neutron flux (n cm^{-2} per proton) on the surface of the middle sections of the U blanket covering a thick Pb target irradiated by 1.5 GeV protons

Neutron energy range (eV)	Neutron flux (n cm^{-2} per proton)	
	Particle detectors	Fission detectors
10^{-2}–10^{4}	2.0 ($\pm$0.4)10^{-3}	
3×10^{5}–3×10^{6}	2.5 ($\pm$ 0.9)10^{-2}	
Above 1×10^{6}		7.5 ($\pm$1.7)10^{-3}

(n, f) and (n,xn) reactions. For (n, γ) reactions, the efficiency is approximately equal to the previous installation. Thus the total transmutation rate possible with the new assembly is enhanced due to the contribution of the fast neutrons. In addition, the neutron fluxes are significantly higher than in the previous installation because the neutron flux along the U blanket surface is almost constant (Fig. 3) while in the Pb cylindrical target it drops towards the upstream and downstream ends [2,3].

4. Conclusion

An experimental transmutation assembly has been built to give high neutron fluxes. The measured neutron fluxes on the surface of the U blanket show a contribution of 10^{-3} thermal neutrons cm^{-2} per 1.5 GeV proton and fast neutrons of 10^{-2} n cm^{-2} per proton. These fluxes are almost constant along the target. The assembly should be efficient for transmutation by (n, f), (n,xn) and (n, γ) reactions. First experiments have been run and other beam energies will be used in order to obtain higher neutron fluxes. The shielding of the assembly has proved quite efficient in reducing fast neutrons by an order of magnitude. Further modifications concerning the fast neutron component could be made during forthcoming runs.

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